Review of a general-purpose sliding-mode control topology for DC/DC converter applications

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***Abstract*— In [1] a sliding-mode control technique for DC/DC converters is proposed with certain benefits over a normal sliding-mode controller. In this paper is investigated if the statements about the proposed controller are true through simulations of a Sepic converter.**

I. INTRODUCTION

Control of DC/DC converters is a widely investigated topic with many control techniques. The most popular among them are *Voltage Control*, *Current Injected Control* and its derivations like *Standard Control Module* and *Average Current Control*. These controllers are simple to implement and easy to design, but their parameters generally depend on the working point. To achieve large signal stability often the bandwidth is reduced resulting in less performance. Moreover, application of these techniques to high-order DC/DC converters (e.g. Ćuk and Sepic topologies) may result in very critical design of control parameters and difficult stabilization. This is the result of the non-linear nature of these converters. To overcome this non-linear behavior, sliding-mode (SM) control can be implemented that has the following advantages- and disadvantages:

Advantages:
- Stability, even for large supply and load variations
- Robustness
- Good dynamic response
- Simple implementation

Disadvantages:
- Varying switching frequency over working points
- Steady-state errors can affect the controlled variables
- Selection of control parameters may be difficult due to the complexity of the sliding-mode control theory

The paper "General-Purpose Sliding-Mode Controller for DC/DC Converter Applications" [1] is describing an adjusted sliding-mode control topology for DC/DC converters that offers certain advantages over a normal sliding-mode controller. The proposed general-purpose SM controller overcomes the drawbacks stated above. In fact:
- Switching frequency is kept constant in the steady state
- Synchronization to external triggers is possible
- Steady-state errors in the output voltage are eliminated
- Control tuning is easy
- Circuitry is simple
- Switch current limitation can easily be implemented
- Robustness against input voltage variations

In this paper the general-purpose sliding-mode controller for DC/DC applications is examined and tested to see if the described statements and advantages are true. This is verified through simulation of both Ćuk and Sepic converter topologies, however only the results of the Sepic converter are discussed in this paper. Also is it stated that this general-purpose sliding-mode controller also works on simpler converter topologies, but verifying this is not in the scope of this paper.

II. ĆUK AND SEPIC CONVERTER TOPOLOGY

There are many DC/DC converter topologies available such as Buck, Boost, Buck-Boost, Ćuk and Sepic. These last two topologies discussed in the paper since they are most interesting, because their complexity makes control design critical. The schematics of these topologies are shown in Figure 1.

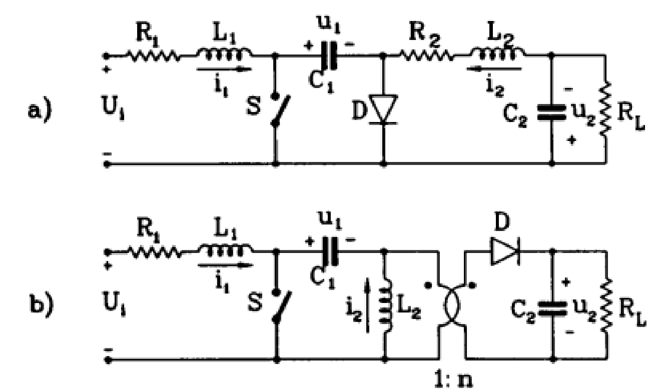

Fig. 1. a) Ćuk converter; b) Sepic converter

Since in the paper the Ćuk converter is only covered briefly by an load step, it is not further discussed here. Extended analysis is only done using a Sepic converter topology.

III. THE GENERAL-PURPOSE SM CONTROL

The schematic shown in Figure 2 shows a normal DC/DC converter sliding-mode controller. As shown all states are measured, increasing the complexity of the controller.

In Figure 3 the general-purpose SM controller is shown where only the inductor current and output voltage are measured. Another difference is the addition of a high-pass filter on the inductor current, a PI controller, trigger (sawtooth) signal w and a current limitation circuit.

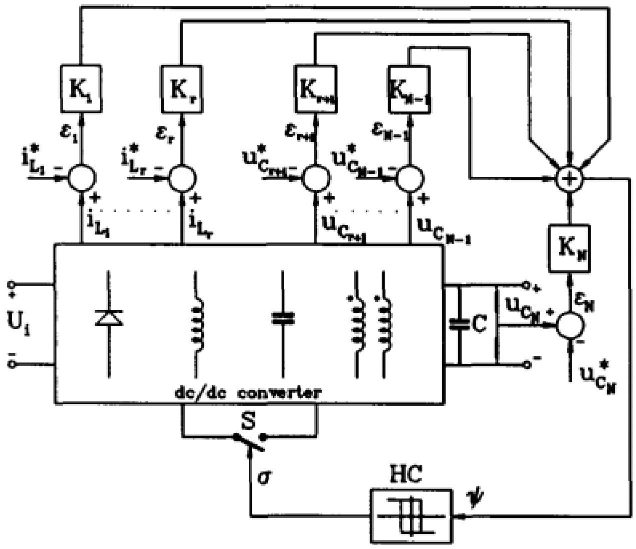

Fig. 2. Principle scheme of a SM controller applied to a generic dc/dc converter

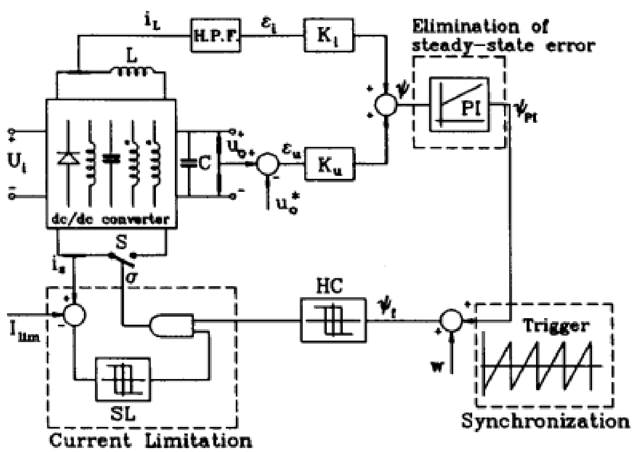

Fig. 3. General-purpose SM controller scheme

In comparison, complexity dropped from measuring five states to only two states using the proposed controller. However a PI controller, sawtooth signal and switch current limiter circuit are added increasing complexity again. Also the switch current must be measured for implementing a switch current limiter. If these circuits are needed is investigated during the simulations later.

IV. Sepic simulation

More in dept analysis of the general-purpose sliding-mode controller is done using the simulation of the given Sepic converter. In these simulations, all control variables of the different subsystems are adjusted to determine the influence on the system behavior. Also are statements about the robustness and steady-state voltage error checked.

The parameters of this converter are shown below:

$$
\begin{array}{ll}
U_i = 15\,[V] & I_{lim} = 3.5\,[A] \\
U_2 = 20\,[V] & f_g = 50\,[kHz] \\
L_1 = 700\,[\mu H] & L_2 = 380\,[\mu H] \\
R_1 = 1\,[\Omega] & C_2 = 100\,[\mu F] \\
C_1 = 6.8\,[\mu F] & R_L = 20 - 200\,[\Omega] \\
K_i = 1.1 & \tau_{HPF} = 0.5\,[ms] \\
K_u = 1 & \tau_{PI} = 0.5\,[ms] \\
n = 1.5 &
\end{array}
$$

Using this converter all parts of the proposed sliding-mode controller are investigated to determine the influence on the system behavior. For this the start-up of the converter and a load step are used to determine the behavior. Using the proposed controller and given converter, the normal behavior is shown in Figure 4. In the simulation start-up is visible, after which a load step occurs at 0.01 second where R_L is changed from 200Ω to 20Ω, and back to 200Ω at 0.015 seconds.

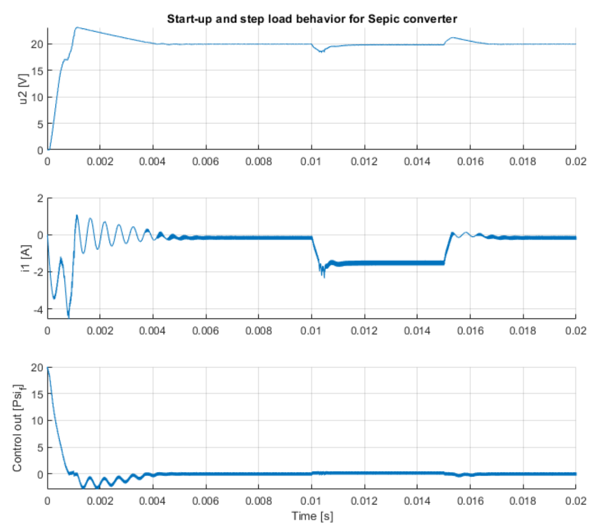

Fig. 4. Standard behavior of given Sepic converter and proposed controller

A. High pass filter

The high-pass filter (HPF) is used to remove the offset from the inductor current, while still passing the current ripple at the switching frequency. One of the requirements for the HPF is that its time constant τ_{HPF} must be 'suitably higher' than the switching period. It is also stated that 'values close to the natural time constants of the system' give the best results. To determine the influence of the HPF, simulations with no HPF, lower time constant, higher time constant and normal time constant are done. Results of these are shown in Figure 5. With no signal w, the switching frequency is not forced in steady-state resulting in a different frequency. When the amplitude of w is lowered the same behavior only occurs during the load step, not in a no-load situation. Increasing the amplitude above the provided value has minimal influence.

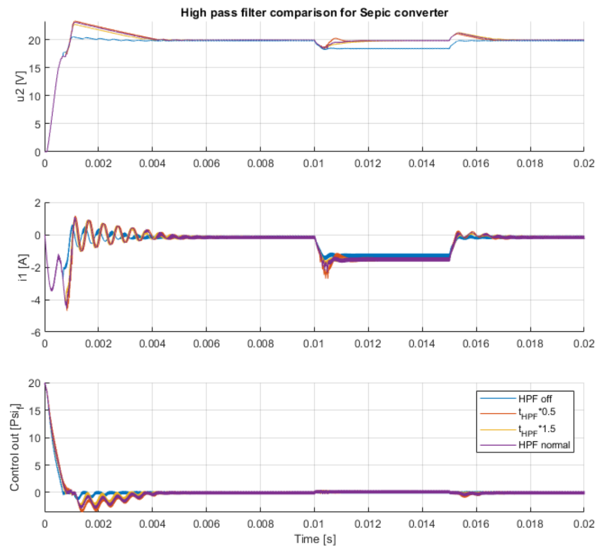

Fig. 5. Comparison of different HPF time constants

B. PI controller

The PI controller is added to eliminate the steady-state error in the output voltage, since the integral part is activated only when the system is on the sliding surface. The inductor current has no effect since its offset is canceled by the high-pass filter. During transients the system behavior is not affected since signal ψ can reach values far from zero. This results in the fast response of SM control. Furthermore it is stated that the time constant of the PI controller in practice τ_{PI} can be set equal to τ_{HPF} and that it is not critical. To determine the difference between no PI control, lower and higher PI controller time constants simulations are executed of which the results are shown in Figure 6. From these results can be concluded that there is no difference between different values for τ_{PI}.

C. Trigger signal w

To provide stabilization of the switching frequency, a saw-tooth signal w at the desired frequency f_w is added to ψ_{PI} resulting in ψ_f. When in steady-state the amplitude of w is predominant in ψ_f a commutation occurs at any cycle of w resulting in an switching frequency equal to f_w. Also does this make it easy to implement synchronization to external triggers since switching is determined by this signal in steady-state. Under dynamic conditions signal w is overridden and the system retains the excellent dynamic response of the sliding mode. To compare what influence different amplitudes of signal w have on the response of the converter simulations are executed. Results of these are shown in Figure 7. The biggest differences are visible during the load step, where both voltage and current ripple increase with a lower amplitude for w.

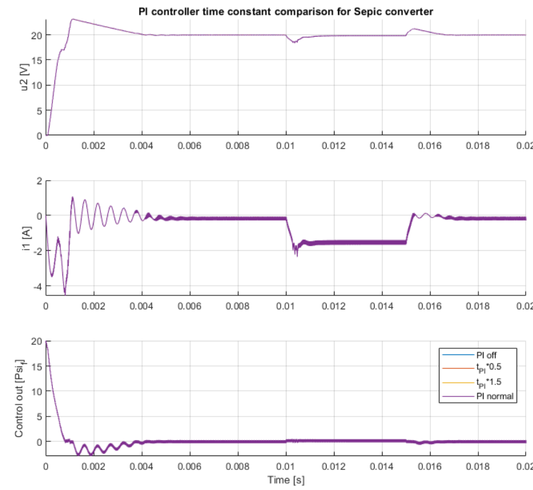

Fig. 6. Comparison of different PI controller time constants

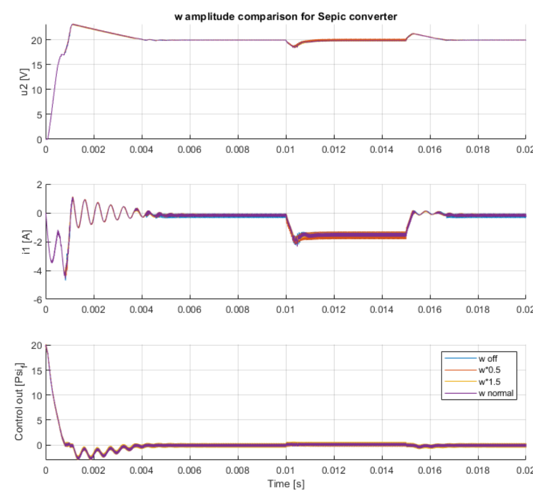

Fig. 7. Comparison of different amplitude levels for signal w

D. Switch current limitation circuit

When switch or inductor current limitation is desired the current limiter circuit as shown in Figure 3 can be implemented. This circuit overrides the SM control when the switch current exceeds threshold I_{lim} and keeps the switch current at its limit. The effect of different current limits during simulations are shown in Figure 8. When there is no current limit, the converter does not start up since the switch immediately closes resulting in maximum current through it, so the current limit circuit is necessary for this converter to work. Furthermore a higher current limit increases the overshoot and a too low current limit causes strange behavior during the load step.

E. Selection of coefficients K_i and K_u

Determining the influence of control values is also done by varying them. For varying K_i the results are shown in Figure

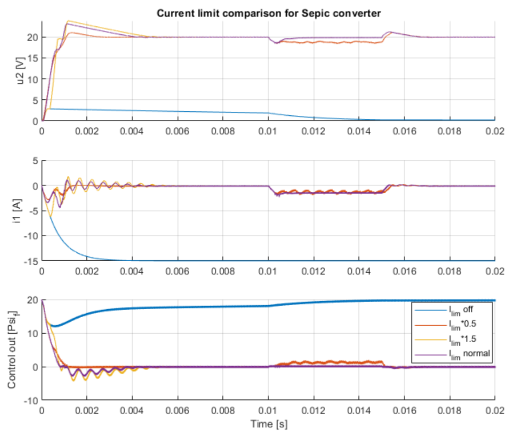

Fig. 8. Comparison of different current limit levels

9 and for K_u in Figure 10. When K_i is disabled by setting it to zero large current and voltage ripples are visible. Also large oscillations are visible when the value is lowered and the response is slower when it is increased. Setting K_u to zero results in large steady-state errors of the output voltage. Lowering it results in a larger overshoot and increasing it results in oscillatory behavior on the signal.

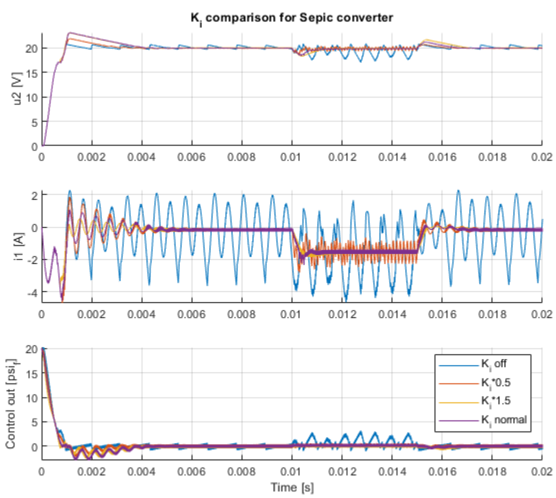

Fig. 9. Comparison of different K_i values

F. Robustness against input voltage variations

In the paper is stated that it is robust against input voltage variations. At a frequency of 100 Hz an AC signal of $4.5V$ (30%) is added to input voltage U_i. This resulted in a ripple of $0.185V$, resulting in a reduction of indeed $-27dB$.

G. Steady-state voltage error

The voltage error in steady-state with no load is about $0.06V$, resulting in an error of $-50dB$. During the load step this increases to $0.2V$, resulting in $-40dB$ steady-state error. While this is a small error, it is not decreasing to 0, indicating there still is a steady-state error.

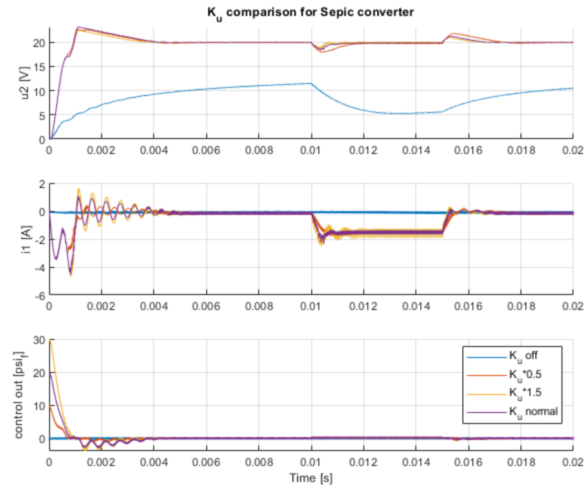

Fig. 10. Comparison of different K_u values

H. Constant switching frequency in steady-state

To determine if the controller has a constant switching frequency in steady-state, a timer is implemented in the simulation. This timer starts counting when the switch is off, from which the switching frequency is determined. The output of the timer is shown in Figure 11 for both load and no-load situations. For both situations the switching period is $20\mu s$, resulting in a switching frequency of $50kHz$ as expected from signal w. Also with an AC disturbance at 100 Hz on the supply voltage the switching frequency remains constant in steady-state.

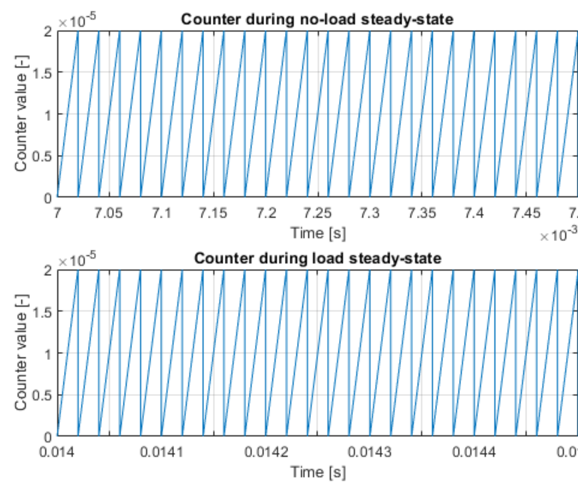

Fig. 11. Continuous switching frequency

V. TUNING

Tuning the sliding-mode controller is also discussed in the paper and is done using sliding-mode control theory. First the converter equations are written in the following form:

$$\dot{\mathrm{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{\sigma} + \boldsymbol{G} \tag{1}$$

where σ is the switch status (1 for closed, 0 for open) and x is the vector of state variables given by $x = v - V^*$. Here $v = [i_1, i_2, u_1, u_2]^T$ are the measured state variables and $V^* = [I_1^*, I_2^*, U_1^*, U_2^*]^T$ represent the vector of their DC references. Matrices A, B and G are listed below.

$$A = \begin{bmatrix} -\frac{R_1}{L_1} & 0 & -\frac{1}{L_1} & -\frac{1}{nL_1} \\ 0 & 0 & 0 & -\frac{1}{nL_2} \\ \frac{1}{C_1} & 0 & 0 & 0 \\ \frac{1}{nC_2} & \frac{1}{nC_2} & 0 & -\frac{1}{R_L C_2} \end{bmatrix} \tag{2}$$

$$\boldsymbol{B} = \begin{bmatrix} \frac{u_1+u_2/n}{L_1} \\ \frac{u_1+u_2/n}{L_2} \\ -\frac{i_1+i_2}{C_1} \\ -\frac{i_1+i_2}{nC_2} \end{bmatrix} \tag{3}$$

$$G = \begin{bmatrix} \frac{-R_1 I_1^* + U_i - (U_1^* + U_2^*/n)}{L_1} \\ L_1 \\ -\frac{U_2^*}{nL_2} \\ \frac{I_1^*}{C_1} \\ \frac{(I_1^*+I_2^*)/n - U_2^*/R_L}{C_2} \end{bmatrix} \tag{4}$$

Since the state feedback $K^T = [K_i, 0, 0, K_u]$ is based on K_i and K_u. Assuming the sliding function is a linear function $\psi = K^T x$ based on i_1 and u_2.

Tuning is done based on three conditions: The existence condition, hitting condition and stability condition. First the *existence condition* is discussed, which is based on the sliding plane of the system as shown in equation 5 for both switch off (top) and switch on (bottom). These equations have to hold for an 'arbitrary' small value of ξ.

$$\begin{aligned} \frac{\partial \psi}{\partial t} &= K^T A x + K^T G < 0 \, for \, 0 < \psi < \xi \\ \frac{\partial \Psi}{\partial t} &= K^T A x + K^T B + K^T G > 0 \, for \, -\xi < \psi < 0 \end{aligned} \tag{5}$$

To study the behavior of the system a vector field is created using the equations from 5 and various states for i_1 and u_2. States i_2 and u_1 are kept in their steady-state values from the earlier provided table and the load resistance is set to 200Ω for ease of simulation. From this figure can be concluded that in steady-state $(u_2 = 20V)$ the current decreases as the switch is open and increases when it is closed, while the voltage is barely adjusted.

For the *hitting condition* the condition $K^T A_4 \leq 0$ has to hold which means that K_u must be zero or positive since it results in $-\dfrac{1}{R_L C_2} K_u \leq 0$.

The *stability condition* needs a linearized model which is not provided by the paper. This introduces an extra step for deriving the control parameters, however it is stated that in practice the parameters are selected 'that ensure stability and provide a good dynamic response'.

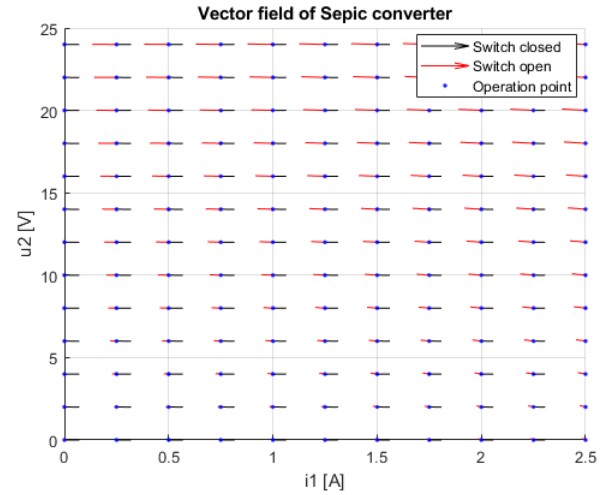

Fig. 12. Sepic converter vector field

From the in the paper provided conditions for selecting the control parameters K_i and K_u it is possible to determine in which region the parameters must be selected, however it is not stated what is the most optimal value nor is it a straight-forward procedure.

VI. CONCLUSIONS

Returning to the statements about the proposed general-purpose sliding-mode controller, in the next part is concluded if they are true or not.

A. Complexity

That this controller has a lower complexity is not completely true, since the measurements of a few states is removed however extra circuitry is added (HPF, sawtooth signal, switch current limiter). However some of these parts add functionalities to the controller but are also needed for it to work, such as the current limiter.

B. Stability

Regarding stability, it is indeed stable for large supply and load variations. The controller has no problem with a load step, also when the supply voltage varies with 30%. However this does not mean that it is robust in practice against parameter variations such as aging capacitors, which is not tested for this assignment.

C. Constant switching frequency in steady-state

The switching frequency in steady-state is indeed constant, also with varying supply voltage.

D. Synchronization to external triggers

Triggering to external signals is indeed possible since the sawtooth signal can be used to synchronize the switching behavior.

E. Steady-state error in output voltage

The steady-state voltage error is during load and no load is below $-40dB$ which is small but does not decrease over time, indicating that there still is an steady-state error in the output voltage. This means that the claim that the steady-state output voltage is canceled is false.

F. Easy switch current limitation implementation

The implementation of the switch current seems easy, however nowhere is stated how the current through the switch is measured. To add this, extra circuitry must be implemented to measure the switch current increasing complexity.

G. Control tuning

A lot of parameters can be varied, such as the HPF, PI controller, sawtooth w, switch current limiter and control gains K_i and K_u. This does make control tuning complicated, but in the paper is explained how to determine the range of these parameters. However it is not explained what parameter combinations lead to optimal performance and from the simulations can be concluded that control tuning is critical for optimal performance. Besides that is stated that most of the time, the parameters are chosen by trial and error in simulation.

H. Overall conclusion

The circuit complexity, steady-state output voltage error and control tuning are debatable, however the other stated benefits about the proposed controller design are true. Also the controller is performing well on the provided Sepic converter in simulations.

REFERENCES

[1] P. Mattavelli, L. Rossetto, G Spiazzi, P. Tenti, ”General-purpose sliding-mode controller for dc/dc converter applications”, 1993 IEEE, pp. 609–615.